Buckling Strength of Slender Steel Plates Stiffened with Corrugated FRP Panels

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ABSTRACT

In this work a novel preformed corrugated FRP section has been developed to strengthen steel web panels against shear buckling. The section of the panel was optimised using finite element modelling that took into account the cost of the FRP material, the quantity of adhesive being used, workmanship, inspection, and the complexity of the multi-axial stress state in the web steel plate, considering potential fatigue and "breathing" issues. Two series of tests were carried out to verify the effectiveness of this corrugated FRP panel in enhancing the shear buckling strength of the web plates of steel plate girders. The variables of these series included the material used (GFRP or CFRP), the number of layers used to produce the FRP panel, the shape and position of the end of the panel and its stiffness. A first series of tests proved the efficiency of the proposed strengthening technique under static loading, and second series aimed to test the efficiency of the optimised FRP panel and its durability under long life cyclic loading. Both series are discussed herein.

INTRODUCTION

For steel girder structures dominated by cyclic loading, as is the case with repeated vehicle axle loads on bridges, web panels buckle at relatively low shear forces because of their slender geometrical properties, usually chosen by designers to reduce the self-weight of the structure, especially in long span bridges. This can lead to the so-called 'breathing' phenomenon; an out-of plane buckling displacement that can induce high secondary bending stresses at the welded plate boundaries. The fatigue performance of the plate girders due to these bending stresses is of particular concern. In this paper, a novel FRP strengthening technique is used to resist the out-of-plane deformations rather than to provide direct tensile stiffness as would be typical in FRP flexural strengthening applications.

Two series of tests were implemented to study the efficiency of the proposed FRP strengthening panels in enhancing the shear buckling strength of steel plate girder web plates. The first series was dedicated to optimizing the bonded FRP section under static loading. Thirteen steel plates were strengthened with preformed corrugated FRP panels of various types and tested using a novel "Picture Frame" testing rig that was designed to restrain the steel plate with the required boundary conditions; applying in-plane shear loads without the need to weld the plate into a frame as in ordinary plate girders. The results of the first series were encouraging, and the proposed strengthening technique demonstrated its effectiveness. The second series was dedicated to testing the effectiveness of an optimised corrugated FRP section under cyclic loading. Six specimens were manufactured to model the end panel of a typical plate girder; three of these were tested under static loading (presented herein) and the other three specimens will be tested for cyclic loading (not presented).

BACKGROUND

Roberts et al. [1] studied the rate of fatigue crack propagation and fatigue limit loads of slender web plates subjected to repeated shear loading. They made the same observations as Yen and Mueller [2], however the results of their tests were presented together with a theoretical procedure for predicting the residual shear strength of fatigue cracked web panels. They noticed that during fatigue tests, the girders exhibited significant plate 'breathing', with pronounced shear buckles forming and reforming along the tension diagonals of the web panels during loading cycles. In general, fatigue cracks formed along the toe of the weld between the web and boundary members, in regions of relatively high secondary bending stresses, as indicated by the out-of-plane deformations. The number of load cycles to fatigue crack initiation (formation of a visual surface or through crack) showed considerable variation. Roberts et al. [3] noted that stress ranges at potential fatigue crack locations can be predicted using nonlinear finite element plate analysis, or by approximate analytical solutions. They also indicated that the fatigue assessment procedures recommended in the Eurocodes, based on either principal stress ranges or normal and shear stress ranges, provide conservative estimates of the fatigue life of slender webs subjected to plate breathing.

To the knowledge of the authors, no research is available in the literature addressing the fatigue problem of FRP strengthened steel plate girders under cyclic shear loading. A limited amount of research is available on strengthening steel plate girders under short term shear loading. One such study was performed by Okeil et. al. [4], who investigated the use of GFRP pultruded sections for strengthening steel plates. In this work GFRP sections were bonded to thin-walled steel plates in orientations that contributed to the out-of-plane stiffness of the plate more than its in-plane strength, as is the common practice in most FRP strengthening applications. Beam (shear) specimens were tested to explore the proposed out-of-plane strengthening technique, which succeeded in increasing the ultimate capacity of the strengthened specimens by 56% over the unstrengthened ones. However, the ductility of the strengthened specimens was reduced as compared to the unstrengthened ones.

OPTIMIZATION OF THE STRENGTHENING TECHNIQUE

Analytical Model

Figure 1 shows the analytical model adopted in this study. The intact steel plate shown in Figure 1-a is a square steel plate of 500×500 mm having a slenderness ratio (h_w / t_w) of 250, where h_w and t_w represent the height and thickness of the steel plate, respectively. Figure 1-b and Figure 1-c show the classical and proposed FRP strengthening techniques, respectively. In the classical technique, several layers (plys) of FRP are bonded to the plate using wet-layup process over the entire area of the steel plate to produce a composite section with marginally stiffer geometrical properties. The proposed strengthening technique in the current study is based on using a preformed corrugated FRP panel, bonded to the compression diagonal of the shear plate providing it with considerably improved geometrical stiffness properties. Preliminary finite element analysis (FEA) suggested that a specimen strengthened with the proposed diagonal corrugated FRP panel had the highest stiffness of the various systems compared, and greatly improved critical buckling shear stress. An attempt was made to choose the best corrugation section to give the highest stiffness and best bond to the steel.

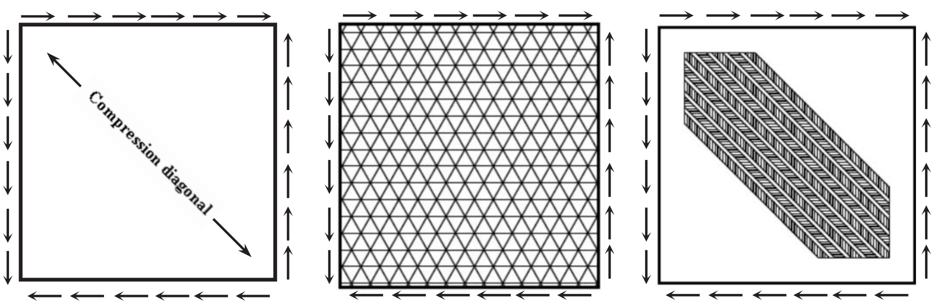

Figure 1-a. Intact steel. Figure 1-b. Classical model. Figure 1-c. Proposed model.

Figure 1. Analytical models adopted in the current study.

Section of FRP Corrugation

Figure 2 shows three types of FRP corrugations, namely: rectangular, circular, and hexagonal, respectively. These three sections were tested numerically using an elastic bucking analysis within Abaqus FEA software. The panels were assumed to be made from GFRP with a thickness of 1.4 mm and a modulus of elasticity of 14.4GPa, and were assumed to be perfectly bonded (i.e. tie constrained) to a steel plate (615 × 245 × 2 mm) having fixed boundary conditions at its top and bottom. This plate represents a compression diagonal strip from the original steel plate shown in Figure 1-c. Reduced integration linear 4-noded shell elements (S4R) were used for both the steel and the FRP in this preliminary model. The results of the preliminary FEA study showed that the Euler critical buckling loads were 10.3kN, 7.3kN, and 8.4kN for the plate strengthened with the rectangular, circular, and hexagonal corrugated sections, respectively. Despite the fact that the rectangular section had the highest buckling load, it was excluded because the sharp edges of this section acted as stress concentrators for both the FRP composite and the bonding strips, and would be more difficult to form. The circular and hexagonal corrugated sections were then selected for further numerical investigation, taking shear buckling into account.

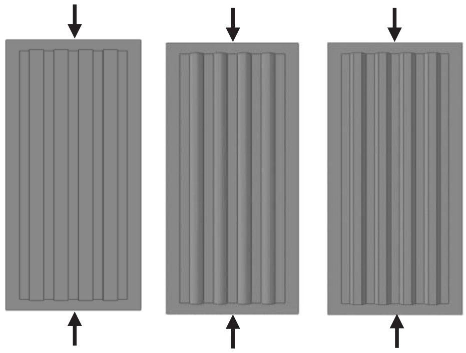

Figure 2-a. Composite section profile.

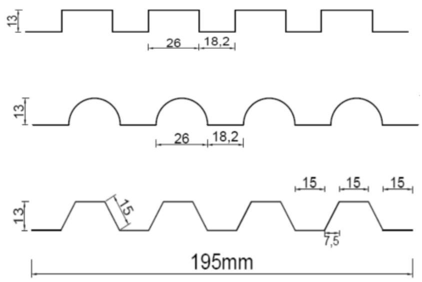

Figure 2-b. FRP panel corrugation sections.

Figure 2. Candidate composite section profiles and sectional dimensions.

Finite Element Analysis

Figure 3 shows the buckling modes for the FEA models of a (500 × 500 × 2 mm) steel plate strengthened with a classical wet-layup GFRP covering the whole surface of the plate (with a thickness of 1.4 mm and a modulus of elasticity of 14.4GPa), along with the same plate strengthened with either the proposed circular or hexagonal corrugated GFRP panels having the same thickness and material properties.. Satisfactory convergence of the model is shown elsewhere [5].

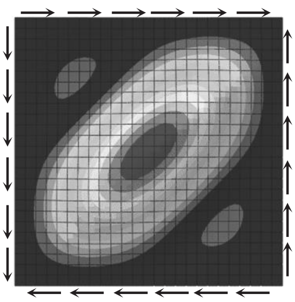

Figure. 3-a. Classical technique.

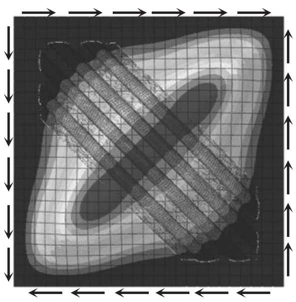

Figure 3-b. Proposed circular section.

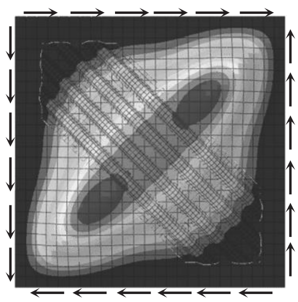

Figure 3-c. Proposed hexagonal section.

Figure 3. Finite element models of classical and proposed strengthening techniques.

The critical buckling shear stresses (σ_{cr}) were 43.5MPa, 114.0MPa, and 122.6MPa, for the classical strengthening technique, proposed circular section, and proposed hexagonal section, respectively. In comparison, σ_{cr} = 42.5MPa for the intact steel plate without strengthening. The new proposed hexagonal corrugated FRP panel demonstrated the highest buckling stress – increasing the buckling stress by a ratio of approximately 3 to 1 – and therefore it was chosen for the experimental study. The proposed preformed corrugated FRP panel succeeded in reducing the amount of required FRP material by approximately 8 times (volumetrically) and the required epoxy for bonding by 7 times as compared with the classical wet lay-up technique.

EXPERIMENTAL PROGRAMME

Table 1 illustrates the material mechanical properties of the FRPs used to produce the panels for the experimental work, where FVF, F_{tf} , and E_{tf} , represent the fibre volume fraction, the tensile strength, and the modulus of elasticity of the fibre composite, respectively. These values were measured experimentally using coupon tension tests. An initial series of 13 steel plates were strengthened by bonding the optimised preformed corrugated FRP panels along their compression diagonals; these were then tested for shear buckling under pseudo-static loading. The in-plane loading was applied using a specially designed ‘picture frame’ testing rig that is capable of holding the steel plate with the required boundary conditions whilst applying in-plane shear loading. Figure 4 shows the picture frame loading rig along with a typical tested plate. Full details of the test series is given in [6].

The second test series involves testing 6 plate girder sections. The clear dimensions of the web panel are 725 × 490 mm, giving an aspect ratio of 1.5. The web plate is made from an S275 steel plate with a thickness of 2 mm. The first 3 specimens were: the control specimen, a GFRP strengthened specimen, and a CFRP strengthened specimen. These were tested for shear buckling under static load to serve as a precursor to the subsequent three tests which will be tested under cyclic loading. Figure 5 shows the specimen details and test set up. Full details of the second test series can be found in [7].

Table 1. FRP Material properties

Specimen	FVF	Ftf, MPa	Etf, GPa	Note
CFRP-450	0.59	758.4	65.4	3-Layers
GFRP-440-45°	0.48	61.9	14.4	3-Layers

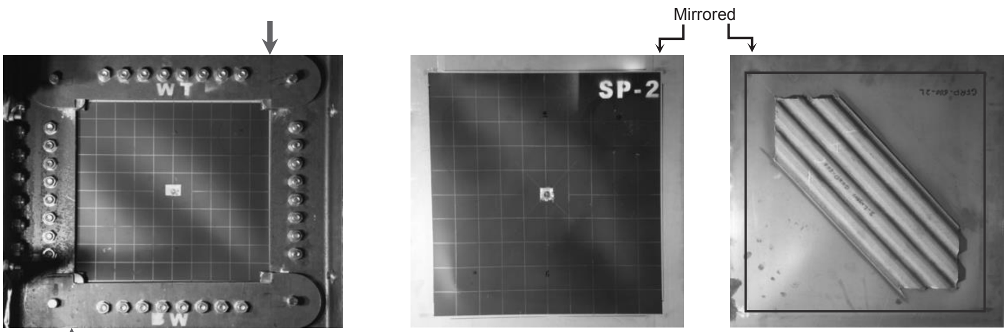

Figure 4. ‘Picture Frame’ testing rig and a typical tested specimen in the initial series.

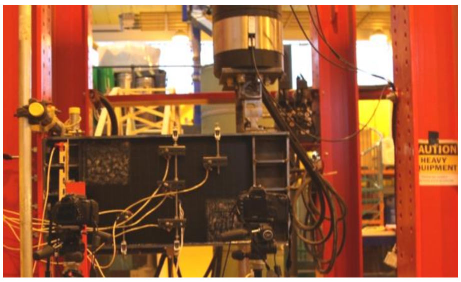

Figure 5-a. Specimen and testing rig.

Figure 5-b. Strengthened specimen.

Figure 5. Details of plate girder specimens used in the second series of tests.

EXPERIMENTAL RESULTS

Figure 6 shows a typical comparison for five FRP strengthened composite plates among the thirteen specimens tested in the initial testing series. These buckling curves confirm the efficacy of the proposed corrugated FRP panel technique in reducing out-of-plane displacements and stiffening the slender plates against shear buckling. Figure 7 shows the results for the tests carried out in the second test series, where (II) stands for the initial imperfection of the web plate, and the dashed lines are hypothetical FEM results that have been included for the sake of comparison. The ultimate load capacity was increased by only 29% and 20% for SP-2 (GFRP) and SP-3 (CFRP), respectively. This can be justified as the designed new strengthening technique is meant for increasing the out-of-plane stiffness of the steel plate and reducing the secondary bending stresses that cause fatigue problems, rather than for increasing the ultimate capacity under pseudo-static loading. However, the maximum surface principal stresses (σ_P) were reduced by 81% and 51% for SP-2 and SP-3, respectively, and the maximum surface principal shear stresses (τ_P) were reduced by 89% and 77%, respectively. A large increase in the stiffness of the strengthened specimens in comparison to the control one was demonstrated by a substantial reduction of the maximum out-of-plane displacements (δ); these were reduced by approximately 90% for both the GFRP and CFRP strengthened specimens. All comparisons were made at a load equal to the control specimen failure load of 87.9 kN. The load was applied in 6 cycles; with each cycle having a stress range increase of 20%. Preliminary fatigue analysis using fatigue strength curves according to Eurocode 3 [8] indicate that the proposed strengthening technique will succeed in prolonging the fatigue life expectation of the bridges by a factor of at least 10:1 [7].

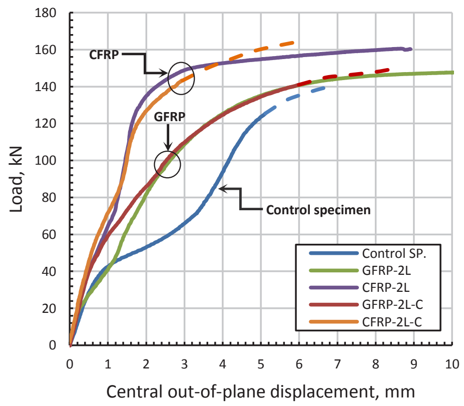

Figure 6. Composite plates tested in the initial series.

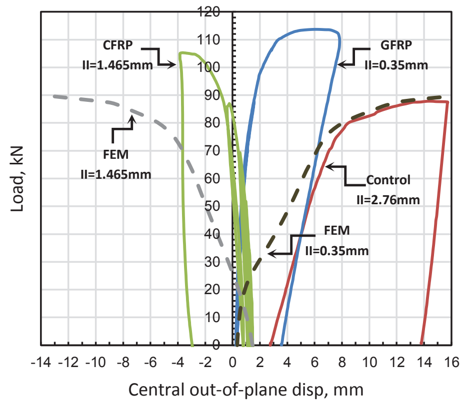

Figure 7. Composite plate girders tested in the final series.

NUMERICAL MODELING

A numerical non-linear FEA model was used to model the experiments. A commercial software package (Abaqus 6.10) was used. Figures 8 and 9 show verification curves for the specimens against central out-of-plane displacement (in-plane deflection and central strain was also verified with the same accuracy). The model was built using S9R5 elements, which are not available in Abaqus standard CAE and can be used only through an Abaqus input file. A Matlab code was written to create the nodes and element incidences and an input file was then created. The initial imperfection was found using the elastic Eigen buckling modes. These were initiated using the buckling analysis available in Abaqus CAE, and then imposed as an initial imperfection using Abaqus script commands in the input file. Elastic-perfectly-plastic stress-strain curves were adopted for the steel constitutive model. Figure 8 indicates that the model was able to predict both the strength and general behaviour of the control specimen with reasonable accuracy both for the loading and unloading stages. An attempt was made to model the GFRP strengthened plate girder using cohesive zone interaction model for the bonding area and an engineering constants material constitutive model for the GFRP corrugated panel. Figure 9 shows that the model succeeded in predicting the behaviour of the specimen up to failure with reasonable accuracy; however, the unloading path remains under consideration. Different failure criteria and composite material constitutive models will be used to simulate these parts in ongoing work.

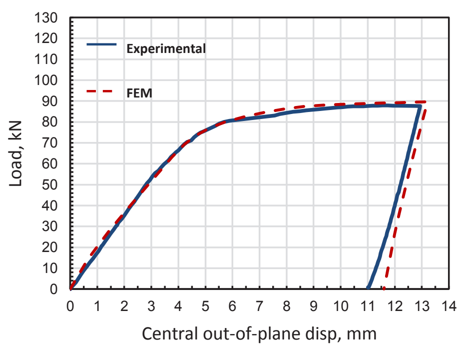

Figure 8. Control specimen.

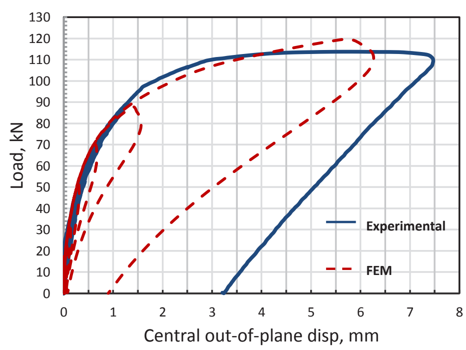

Figure 9. GFRP strengthened specimen.

CONCLUSIONS

A novel preformed corrugated FRP panel has been introduced in this study as a strengthening technique for slender steel plates – such as the webs of a plate girder – against breathing of plates, possibly leading to fatigue failures. The section of the panel was optimised using extensive finite element modelling that took into account minimizing the cost of the FRP material, the quantity of adhesive being used, workmanship, and the complexity of the multi-axial stress state in the web steel plate.

Two series of experimental studies were performed. The first series was to test the effectiveness of the proposed corrugated FRP strengthening panels under static loading. The test variables in this series included the material used (GFRP or CFRP), the number of layers used to produce the FRP panel, the shape and position of the end of the panel, and the stiffness of the FRP panel. Thirteen steel plates were strengthened with the proposed FRP panels and tested using a special 'picture frame' testing rig, which was designed to hold the steel plate in position with the required boundary conditions. The results of the first series demonstrated the effectiveness of the proposed strengthening technique. The second series tested the effectiveness of the optimised corrugated section resulting from the first series, however under cyclic loading. Six specimens were fabricated to model the end panel of a typical plate girder; three of them were tested under static loading to serve as a precursor for the other three specimens which will be tested for cyclic loading.

Preliminary fatigue analyses indicate that the proposed strengthening technique should be able to considerably reduce the secondary bending stresses at the web plate welded boundaries, and therefore elongate the life expectancy of some plate girders by a factor of 10.

A geometrical and material non-linear FEA in commercial software was used to model the specimens used in this study and the proposed strengthening techniques. The unstrengthened model yielded reasonable results and was able to simulate the behaviour of the specimen throughout all loading stages, including unloading stage. The strengthened model worked only up to the failure plateau, and the unloading path is being considered in on-going work. Once the model is properly validated against test results it will be used for parametric studies and as the basis to propose design guidelines.

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